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TECHNICAL NOTE

No. 1104

EXPERIMENTAL DETERMINATION OF THE EFFECTS OF
DIRECTIONAL STABILITY AND ROTARY DAMPING IN
YAW ON LATERAL STABILITY AND
CONTROL CHARACTERISTICS

By Hubert M. Drake

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SUMMARY

The effects of large variations of the directional-stability derivative $C_{n\beta}$ (rate of change of yawing-moment coefficient with angle of sideslip) and the rotary-damping-in-yaw derivative C_{nr} (rate of change of yawing-moment coefficient with yawing-angular-velocity factor) on the lateral stability and control characteristics of a free-flying model have been determined by flight tests in the Langley free-flight tunnel. The effects of each parameter were investigated for three values of the lateral-force derivative $C_{Y\beta}$ (rate of change of lateral-force coefficient with angle of sideslip). In the tests the ailerons were used as the principal lateral control.

Increasing C_{nr} for medium or large values of $C_{n\beta}$ and $C_{Y\beta}$ was found to improve the stability but to have little effect on control and general flight behavior. At low values of $C_{n\beta}$ for low and moderate values of $C_{Y\beta}$, moderate increases in C_{nr} slightly improved the control and flight behavior but larger increases caused the control, and hence the flight behavior, to become worse.

Increasing $C_{n\beta}$ was found to be beneficial to stability and control in all tests. The value of $C_{n\beta}$ required to obtain satisfactory flight depended to some

extent on the accompanying value of $C_{Y\beta}$; larger values of $C_{n\beta}$ were required to obtain good flights with large values of $C_{Y\beta}$ than with small values of $C_{Y\beta}$.

INTRODUCTION

Some question has been raised as to the probable lateral stability and control characteristics of airplanes having relatively low values of the directional-stability derivative $C_{n\beta}$, the rotary-damping-in-yaw derivative C_{nr} , and the lateral-force derivative $C_{Y\beta}$. Interest in the effects of these derivatives has increased recently with the design of several airplanes having small values of some of these derivatives. An investigation has been conducted, therefore, in the Langley free-flight tunnel of the effects of independent variation of $C_{n\beta}$, C_{nr} , and $C_{Y\beta}$ on the stability and control of a flying model. The part of the investigation that dealt with the effects of $C_{Y\beta}$ has been previously reported in reference 1. The present paper describes the results of the investigation of the effects of $C_{n\beta}$ and C_{nr} for zero dihedral.

Changes in the values of $C_{n\beta}$, C_{nr} , and $C_{Y\beta}$ were obtained by various combinations of vertical-surface area and tail length so that one derivative could be varied while the other two were held approximately constant. The aerodynamic characteristics of the various flight configurations were determined by force tests and free-oscillation tests.

SYMBOLS AND COEFFICIENTS

The forces and coefficients were measured with reference to the stability axes. A diagram of these axes showing the positive directions of forces and moments is presented as figure 1. The forces and coefficients used in the present paper are as follows:

C_L	lift coefficient $\left(\frac{\text{Lift}}{qS}\right)$
C_L	rolling-moment coefficient $\left(\frac{\text{Rolling moment}}{qSb}\right)$
C_n	yawing-moment coefficient $\left(\frac{\text{Yawing moment}}{qSb}\right)$
C_Y	lateral-force coefficient $\left(\frac{\text{Lateral force}}{qS}\right)$
S	wing area, square feet
b	wing span, feet
q	dynamic pressure, pounds per square foot $\left(\frac{1}{2}\rho V^2\right)$
V	airspeed, feet per second
y	sidewise displacement, feet
ρ	mass density of air, slugs per cubic foot
t	time, seconds
β	angle of sideslip, degrees
ψ	angle of yaw, degrees (for force-test data, $\psi = -\beta$)
ϕ	angle of bank, degrees
δ_s	stabilizer setting, degrees
δ_e	elevator deflection, degrees
L	rolling moment, about X-axis
N	yawing moment, about Z-axis
M	pitching moment, about Y-axis
δ_r	rudder deflection, degrees
α	angle of attack, degrees
$T_{1/2}$	time for oscillation to damp to one-half amplitude, seconds

- P period of lateral oscillation, seconds
- k_X radius of gyration about X-axis, feet
- k_Z radius of gyration about Z-axis, feet
- $pb/2V$ helix angle generated by wing tip in roll, radians
- p rolling angular velocity, radians per second
- r yawing angular velocity, radians per second
- $C_{l\beta}$ effective-dihedral derivative, that is, rate of change of rolling-moment coefficient with angle of sideslip, per degree $\left(\frac{\partial C_l}{\partial \beta}\right)$
- $C_{n\beta}$ directional-stability derivative, that is, rate of change of yawing-moment coefficient with angle of sideslip, per degree $\left(\frac{\partial C_n}{\partial \beta}\right)$
- C_{nr} rotary-damping-in-yaw derivative, that is, rate of change of yawing-moment coefficient with yawing-angular-velocity factor, per radian $\left(\frac{\partial C_n}{\partial \left(\frac{rb}{2V}\right)}\right)$
- $C_{Y\beta}$ lateral-force derivative, that is, rate of change of lateral-force coefficient with angle of sideslip, per degree $\left(\frac{\partial C_Y}{\partial \beta}\right)$

APPARATUS AND MODEL

The tests were conducted in the Langley free-flight tunnel described in reference 2. Force tests were made on the free-flight-tunnel six-component balance described in reference 3 and free-oscillation tests to determine C_{nr} were made on the apparatus described in reference 4.

A three-view sketch of the model used in the tests is shown as figure 2 and a photograph of the model is shown as figure 3. The test model was so designed that vertical tails of different size (fig. 2) could be mounted at various locations along the fuselage, both ahead of and behind the center of gravity. The fuselage was designed to contribute as little lateral force as possible in order to test small values of $C_{Y\beta}$. The dimensional and mass characteristics of the model are presented in table I.

TESTS

Range of Tests

The range of test conditions covered in the investigation is shown in figure 4 in the form of slope values obtained from the force and free-oscillation tests of the model in various conditions. The derivatives $C_{n\beta}$ and C_{nr} were varied for three values of $C_{Y\beta}$ (-0.0044, -0.0105, and -0.0205). Changes in $C_{n\beta}$, C_{nr} , and $C_{Y\beta}$ were obtained by various combinations of vertical-surface area and tail length so that one parameter could be varied while the other two were kept approximately constant.

Flight tests were made at a lift coefficient of 0.5 for each of the conditions represented by the test points shown in figure 4.

The ailerons were used as the principal control for most of the flights with the rudder either fixed or coordinated with ailerons. A few flights were made with independent rudder and aileron control to determine the effects of this type of control on the flight characteristics of some of the configurations tested. For conditions in which the rudder control was not available, the ailerons were trimmed up 10° in order to reduce the adverse yawing due to the ailerons. The ailerons were also trimmed up for some conditions in which rudder control was available in order for smaller rudder deflections to be used to eliminate the adverse yawing. The total aileron deflection used in the tests was 30° . This

deflection gave a value of $pb/2V$ of about 0.07, as measured in rolls from level flight with rudder fixed.

Flight tests were made at an effective dihedral angle of approximately 0° as measured by force tests. Inasmuch as the vertical tail contributes to the effective dihedral, the vertical tails required for the various configurations were added above or below the fuselage in order to maintain the effective dihedral angle as near 0° as possible.

Throughout the tests the mass characteristics were maintained constant at the values given in table I.

Technique of Testing

Two methods of lateral control were used during the tests. The first method was the normal means of control, in which the aileron and rudder were coordinated to deflect at the same time and in which provision was made for fixing the rudder in the neutral setting. In this way, flights were possible with ailerons alone. This means of control is referred to as "coordinated control" and, unless otherwise stated, was the type of control used in the tests. The other method consisted of applying aileron and rudder control independently. Using this control the pilot could at will apply the rudder either alone, against, or with the ailerons. This type of control is referred to as "independent aileron and rudder control." In both of these methods the aileron and rudder deflected abruptly to full travel when the control was applied.

The model was flown at each of the test conditions represented by the parameter values in figure 4. Graduated ratings on stability, control, and general flight characteristics were assigned each test condition from the pilot's observations of the model in flight. The stability and control ratings used were as follows:

Rating	Stability or control
A	Good
B	Fair
C	Poor
D	Very poor

Plus or minus ratings were assigned to indicate slight but perceptible changes in the rating. Motion-picture records of some flights were made to permit more careful study of the flight characteristics and thereby to aid observers in making more accurate flight ratings.

The stability of a free-flying model in the Langley free-flight tunnel is generally determined from the steadiness of flight in the rather gusty air of the tunnel. A very stable model returns to its original flight path more rapidly after receiving a gust disturbance and generally does not tend to move as far from its original flight path as one with less stability. Greater stability is thus indicated by greater steadiness. For unstable conditions the degree of instability is judged from the rate at which the model deviates from a straight and level flight and from the frequency of control application required to maintain steady flight.

The control rating is determined from the ease with which straight and level flight is maintained and from the response of the model to control applications designed to perform maneuvers. Any unnatural lag or motion in the wrong direction is judged as poor control.

The general flight-behavior ratings, graduated from excellent to unflyable, are based on the over-all flying characteristics of the model. The ratings indicate the ease with which the model can be flown, both for straight and level flight and for performance of the mild maneuvers possible in the tunnel. Any abnormal characteristics of the model are judged as poor general flight behavior when they are disconcerting to the free-flight-tunnel pilots.

RESULTS AND DISCUSSION

The results of the investigation to determine the effects of C_{n_r} and C_{n_β} are shown in figures 5 and 6, which present pilot's ratings for the stability, control, and general flight characteristics for the test points shown in figure 4. It should be remembered that these results were obtained for an effective dihedral angle of 0° ($C_{l_\beta} = 0$) and are strictly true only for this dihedral. The trends shown herein, however, are believed

to be independent of the dihedral. The effects of dihedral have been reported in reference 5.

Since completely separating the effects of the three parameters $C_{n\beta}$, C_{nr} , and $C_{Y\beta}$ is impossible, some of the data reported in reference 1 are referred to in this paper. For a complete discussion of the effects of $C_{Y\beta}$, reference 1 should be used.

Effect of C_{nr}

Effect of C_{nr} on stability.— Figure 5 shows that a slight increase in stability occurred as C_{nr} was increased for all three values of $C_{Y\beta}$ at all but the smallest values of $C_{n\beta}$. Calculations of the variation in period and damping of the lateral oscillation with changing C_{nr} were made by the method of reference 6 for a value of $C_{Y\beta} = -0.0105$ and are presented in figure 7. These calculations agree with the experimental results; that is, increasing C_{nr} increases the damping of the oscillation and thereby increases the stability of the model. In general, the effects on stability of varying C_{nr} were similar to those of varying $C_{Y\beta}$ reported in reference 1.

Effect of C_{nr} on control.— The effect on control of varying C_{nr} is shown in figure 6 to be small and to be dependent upon the accompanying value of $C_{n\beta}$. For the largest values of $C_{n\beta}$ tested, very little change was noted in the control with increased C_{nr} . At the lowest values of $C_{n\beta}$ for low and moderate values of $C_{Y\beta}$, the model control improved with moderate increases in C_{nr} but became worse with larger increases in C_{nr} . This result might be explained as follows: At very low values of $C_{n\beta}$ the model yawed to large angles as a result of gusts or control deflections.

A moderate increase in C_{n_r} caused a noticeable improvement in flight behavior by increasing the stability and thus reducing the frequency of control application required to maintain steady flight. Still further increases in C_{n_r} , however, increased the stability to such an extent that, once the model reached a large angle of yaw, the high damping caused the return to zero yaw to be so slow that difficulty was encountered in controlling the model by use of the ailerons.

At the low values of C_{n_β} and C_{Y_β} some flights were made to determine how the use of "independent aileron and rudder control" would alter the effects of C_{n_r} on general flight characteristics. Flights with this means of control were made by two methods: (1) the ailerons were used to hold the wings level while the rudder was used to move the model laterally in the tunnel, and (2) the rudder was used to maintain zero sideslip while the ailerons were used to move the model laterally in the tunnel. At low values of C_{n_r} the control as described in methods (1) and (2) was about the same as that with "coordinated control," the normal means of control. With the large values of C_{n_r} , method (2) showed a marked improvement in control over the "coordinated control" but method (1) gave slightly worse control characteristics. This result was obtained because the rudder control over the sidewise motion was extremely slow and much less effective than aileron control.

Effect of C_{n_r} on general flight characteristics.-

The ratings of the general flight characteristics are presented in the control-rating charts of figure 6 as separated regions. These ratings indicate that C_{n_r} had very little effect on the general flight behavior except at the lowest values of C_{n_β} for the low and moderate values of C_{Y_β} . At these values, moderate increases in C_{n_r} improved the general flight behavior of the model. With further increases in the value of C_{n_r} , however, the flight ratings became lower because of the deterioration in the controllability at large values of C_{n_r} .

Effect of $C_{n\beta}$

The effect of $C_{n\beta}$ on the stability and control of the model is shown in figures 5 and 6. Increasing $C_{n\beta}$ was found, in general, to be beneficial to both stability and control.

The beneficial effect of $C_{n\beta}$ was modified to a considerable extent by the accompanying values of $C_{Y\beta}$ and, to a lesser extent, by the accompanying values of C_{n_r} . An increase in the value of $C_{Y\beta}$ from -0.0044 to -0.0205 required about a 100 percent increase in the value of $C_{n\beta}$ to maintain a general flight rating of good. For any value of $C_{Y\beta}$ in the range tested, a value of $C_{n\beta}$ of about 0.0014 was required to obtain fairly satisfactory flights. A value of $C_{n\beta}$ of about 0.0022 was required, however, to obtain entirely satisfactory flights.

In flights made at the lowest stable values of $C_{n\beta}$ and $C_{Y\beta}$ the model was very controllable, but the flights were characterized by a long-period large-amplitude yawing oscillation that was objectionable to the pilot. This objectionable yawing oscillation offset the good control to some extent and thus affected the general flight rating. For example, the point ($C_{Y\beta} = -0.0044$, $C_{n\beta} = 0.00014$, $C_{n_r} = -0.085$) was given a control rating of good but a general flight-behavior rating of barely fair.

Time histories of flights made at a low value of $C_{n\beta}$ are shown in figure 8. These flights were made in the course of the investigation reported in reference 1; therefore the values of $C_{Y\beta}$ are not the same as in the present investigation. The flight behavior shown by these records, however, is very similar to that noted in the present tests. The

large-amplitude yawing oscillation shown in the motion-picture records has been previously reported for other airplanes (model and full-scale tailless designs) having small values of $C_{n\beta}$ and $C_{Y\beta}$ and was similarly objectionable to both free-flight-tunnel and airplane pilots. The record of control application shows that the model with low $C_{Y\beta}$ was very controllable, requiring only an occasional brief flick of the controls. When $C_{Y\beta}$ was increased to the larger value, the model was barely flyable and relatively insensitive to control. These effects of $C_{Y\beta}$ are described more completely in reference 1.

A motion-picture record of a flight made with negative directional stability is presented in figure 9. The model in this condition was directionally unstable but the divergence was relatively slow. Although the divergence was not affected by the aileron control, the model could probably have been controlled by use of independent rudder. For this configuration, however, independent rudder control was not available.

CONCLUSIONS

The results of tests conducted in the Langley free-flight tunnel to determine the effects of the rotary-damping-in-yaw derivative C_{nr} (rate of change of yawing-moment coefficient with yawing-angular-velocity factor) and the directional-stability derivative $C_{n\beta}$ (rate of change of yawing-moment coefficient with angle of sideslip) on lateral stability and control characteristics may be summarized as follows:

1. Increasing C_{nr} increased the stability of the model but had little effect on the control or general flight behavior for all but the lowest values of $C_{n\beta}$ and $C_{Y\beta}$ (rate of change of lateral-force coefficient with angle of sideslip). At low values of $C_{n\beta}$ for low and moderate values of $C_{Y\beta}$, moderate increases in C_{nr} slightly improved the control and flight behavior but larger increases caused the control, and hence the flight behavior, to become worse.

2. In general, increasing $C_{n\beta}$ was beneficial to stability and control. The value of $C_{n\beta}$ required for satisfactory flight characteristics was found to depend to some extent on the accompanying values of $C_{Y\beta}$; larger values of $C_{n\beta}$ were required to obtain good flights with large values of $C_{Y\beta}$ than with small values of $C_{Y\beta}$.

3. At large values of C_{nr} for small and moderate values of $C_{n\beta}$ and $C_{Y\beta}$, the control was improved by the use of independent aileron and rudder, if the rudder was used to maintain zero sideslip while the ailerons were used to maneuver the model. When the ailerons were used to hold the wings level while the rudder was used to maneuver the model, the model was more difficult to control than when the ailerons alone were used.

Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., March 27, 1946

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TABLE I

MASS AND DIMENSIONAL CHARACTERISTICS OF MODEL

Weight, lb	5.03
Wing	
Area, sq ft	2.67
Span, ft	4.0
Aspect ratio	6.0
Mean aerodynamic chord, feet	0.70
Sweepback of 50-percent-chord line, deg	0
Dihedral, deg	0
Taper ratio (ratio of tip chord to root chord)	0.50
Root chord, ft	0.90
Tip chord, ft	0.45
Loading, lb/sq ft	1.39
Radii of gyration	
k_x , ft	0.625
k_z , ft	0.844
Aileron	
Type	Plain
Area, percent S	7
Span, percent b	4.0

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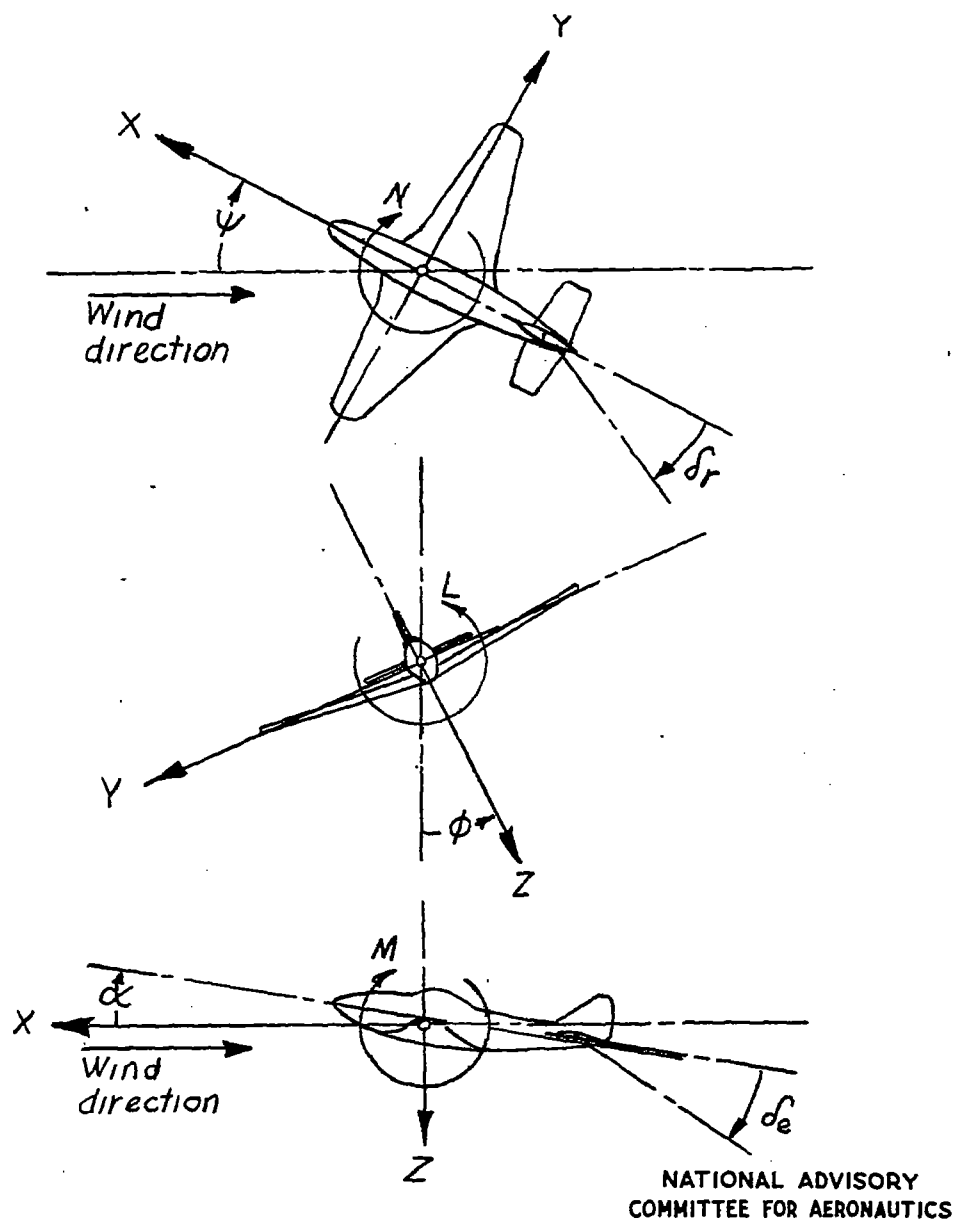


Figure 1.-The stability system of axes. Arrows indicate positive directions of moments, forces, and control-surface deflections. This system of axes is defined as an orthogonal system having their origin at the center of gravity and in which the Z-axis is in the plane of symmetry and perpendicular to the relative wind, the X-axis is in the plane of symmetry and perpendicular to the Z-axis, and the Y-axis is perpendicular to the plane of symmetry.

Fig. 2

NACA TN No. 1104

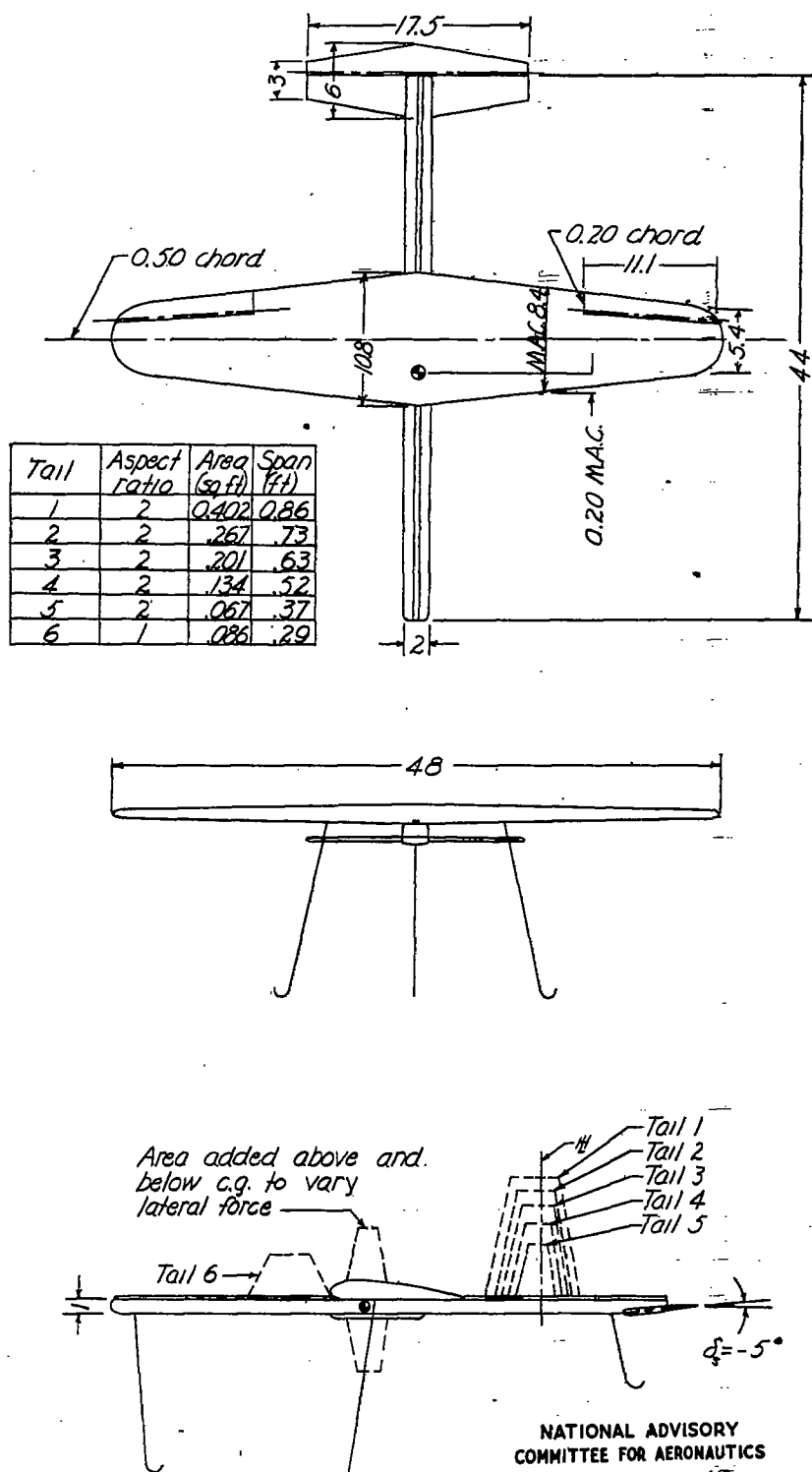


Figure 2.-Three-view sketch of model used in lateral-stability investigation. All dimensions are in inches.

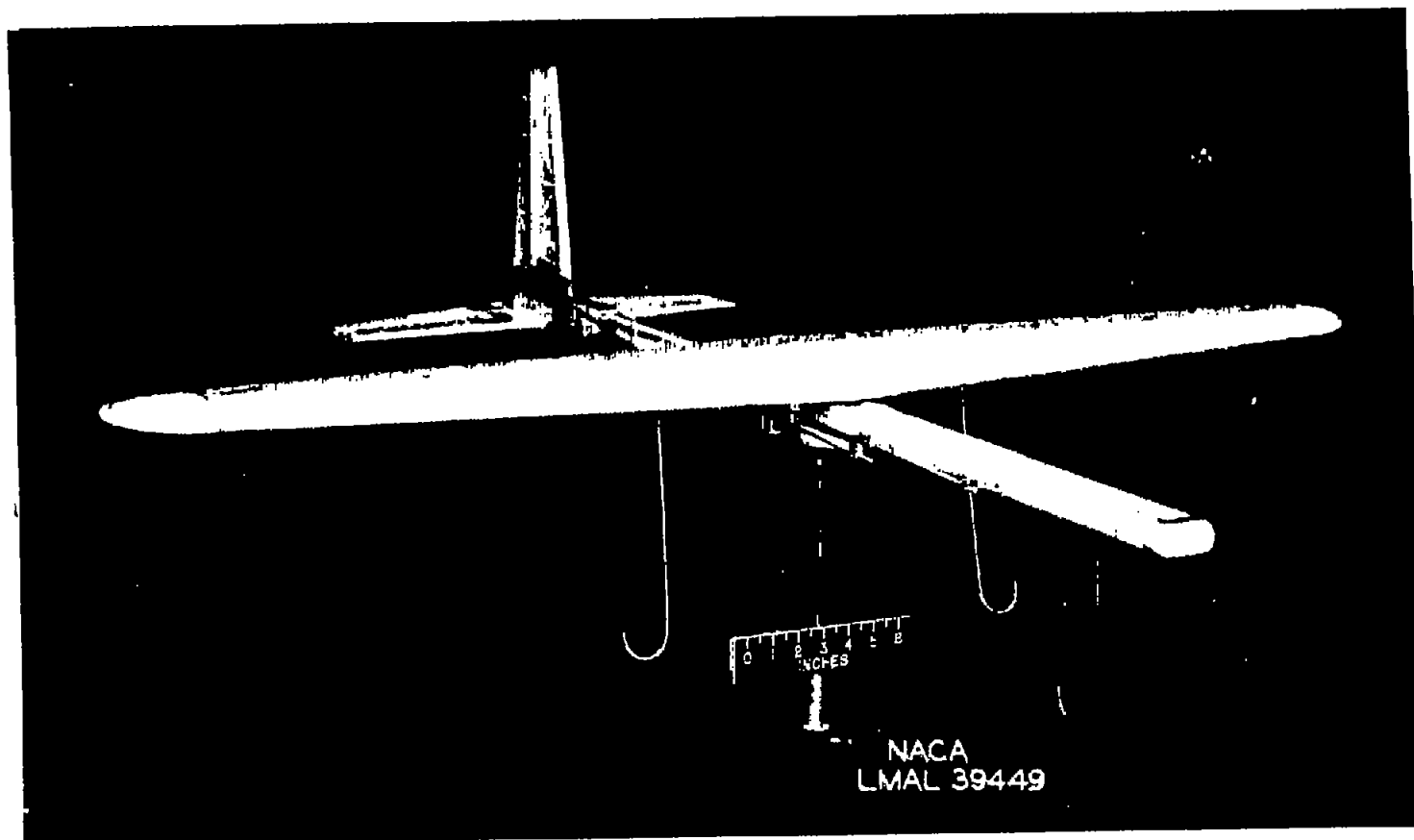


Figure 3.- Three-quarter front view of model used in rotational-damping and directional-stability investigation in Langley free-flight tunnel showing tail 1 installed.

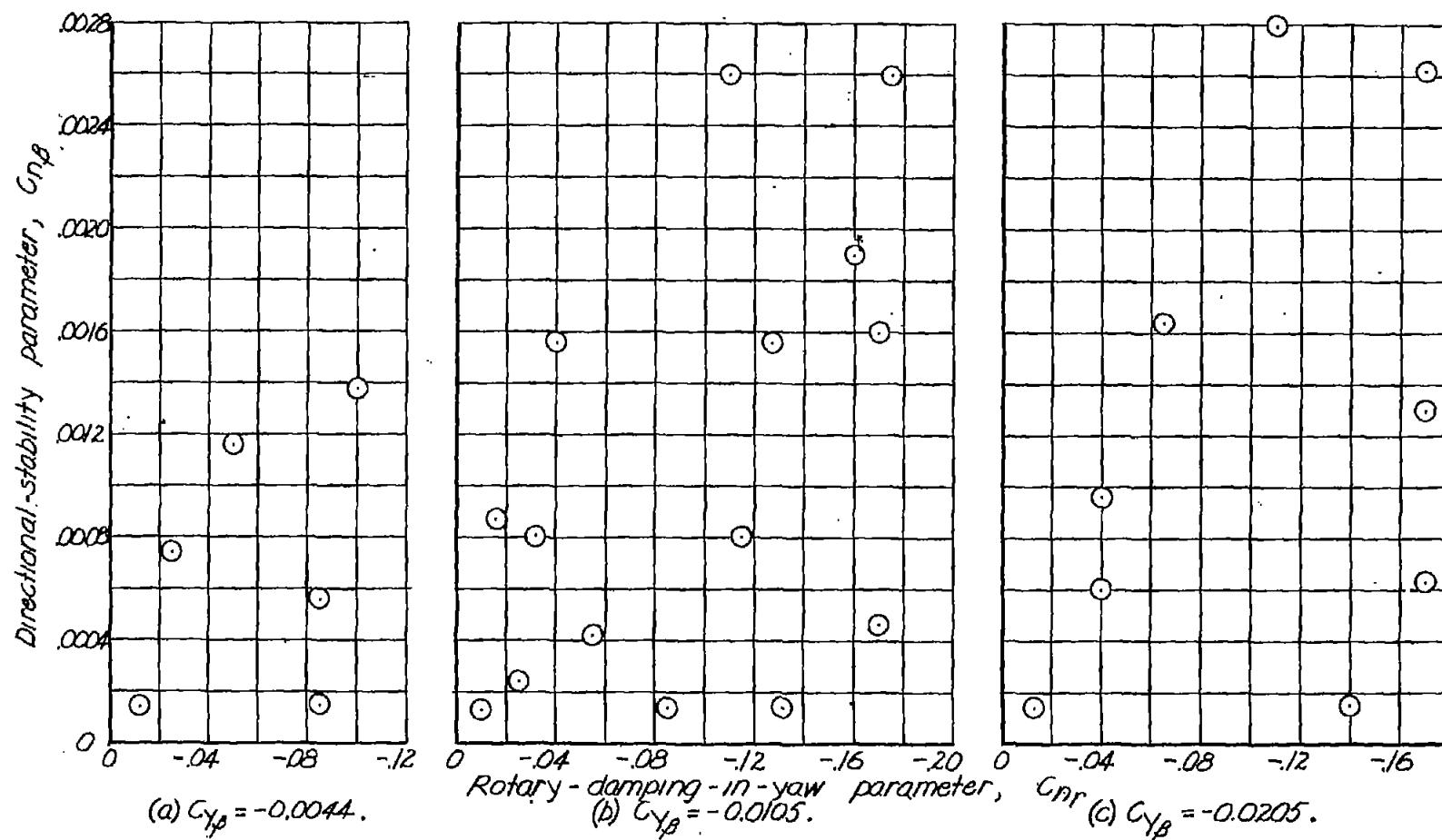


Figure 4. - Range of values of C_{nr} and $C_{n\beta}$ covered in rotational-damping and directional-stability investigation. $C_L = 0.5$.

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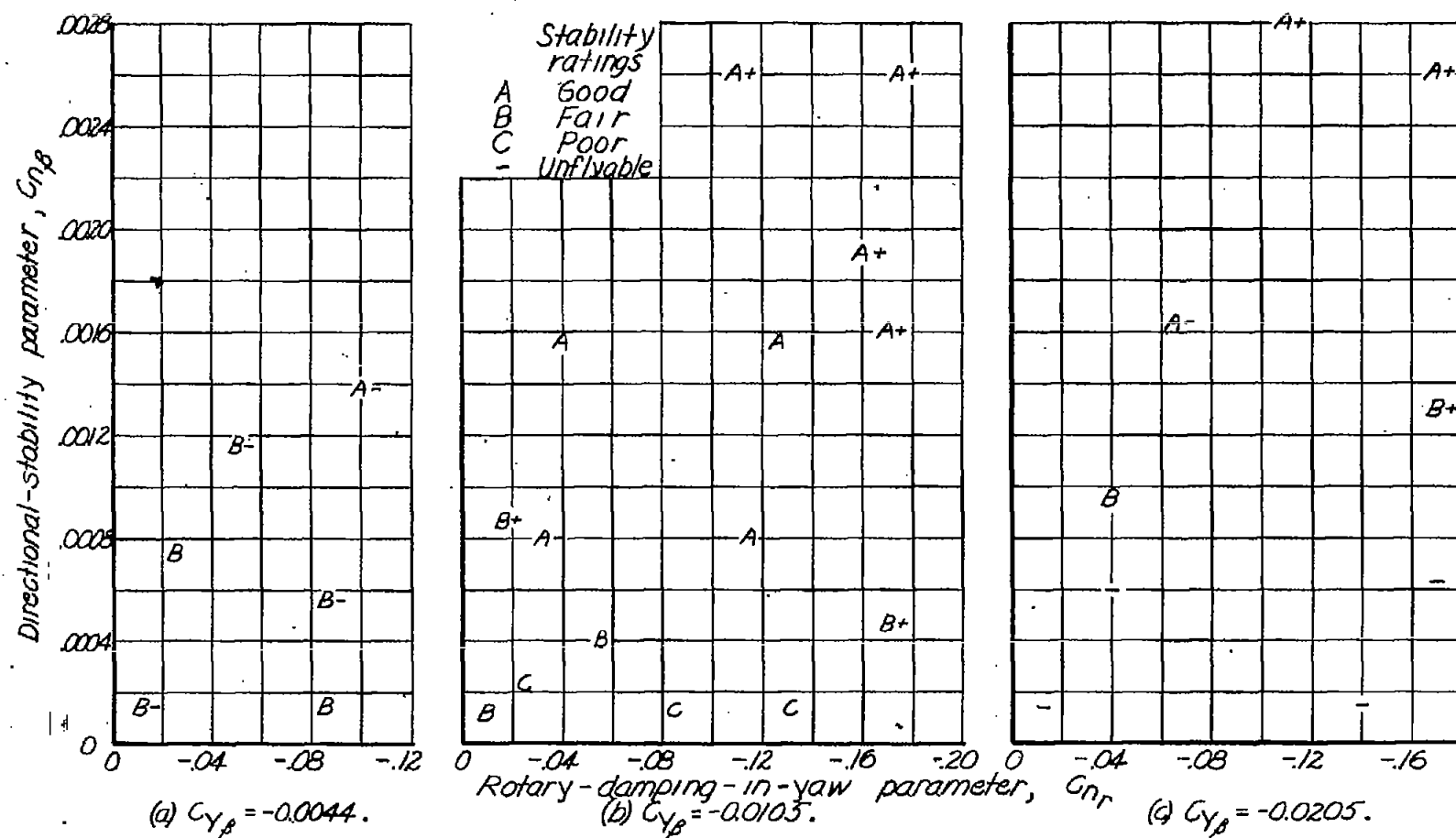


Figure 5.- Effects of rotary damping in yaw and directional stability on the stability of the model. $C_L = 0.5$.

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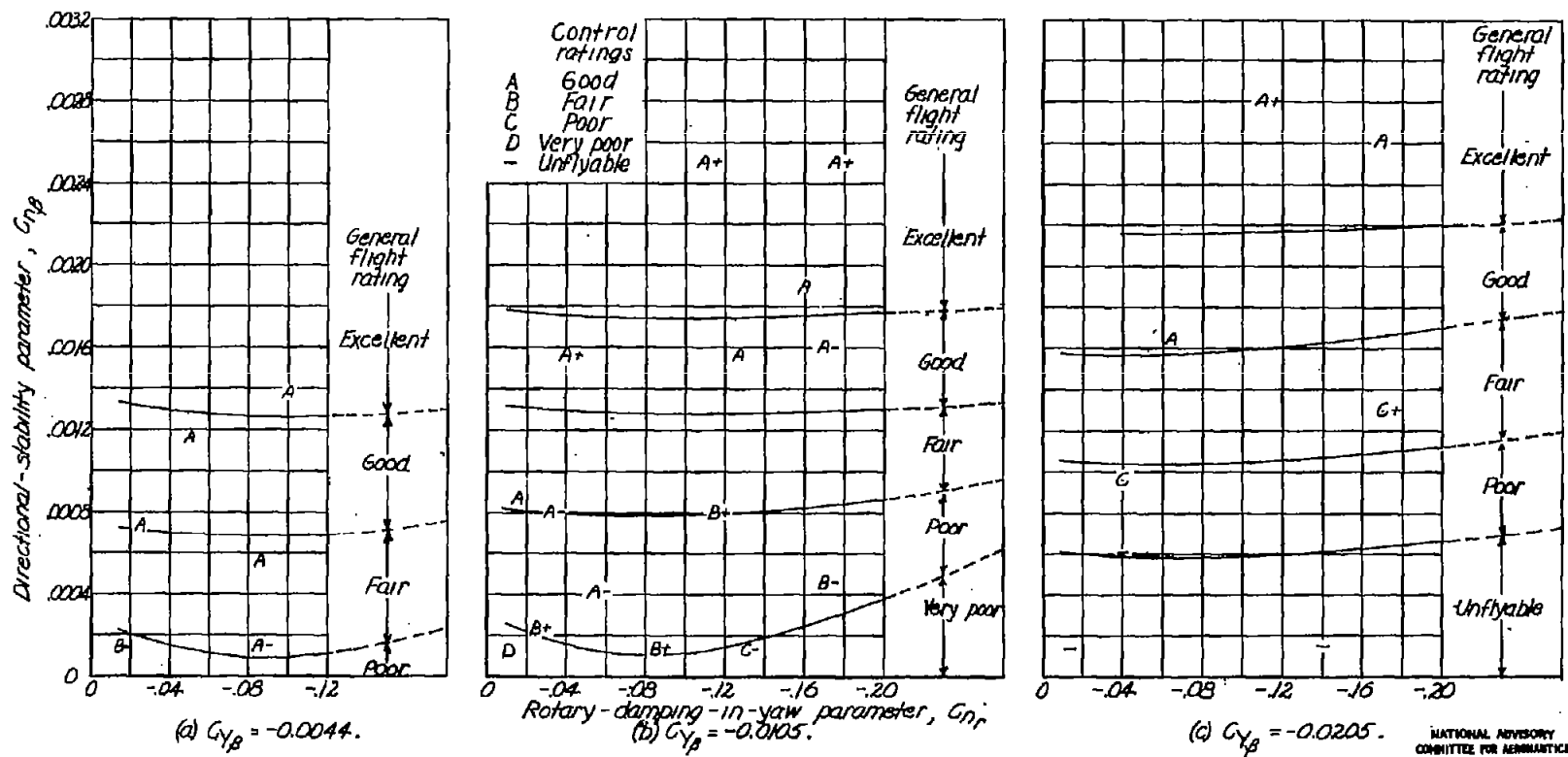


Figure 6.—Effects of rotary damping in yaw and directional stability on the control and general flight behavior of the model. $C_L = 0.5$.

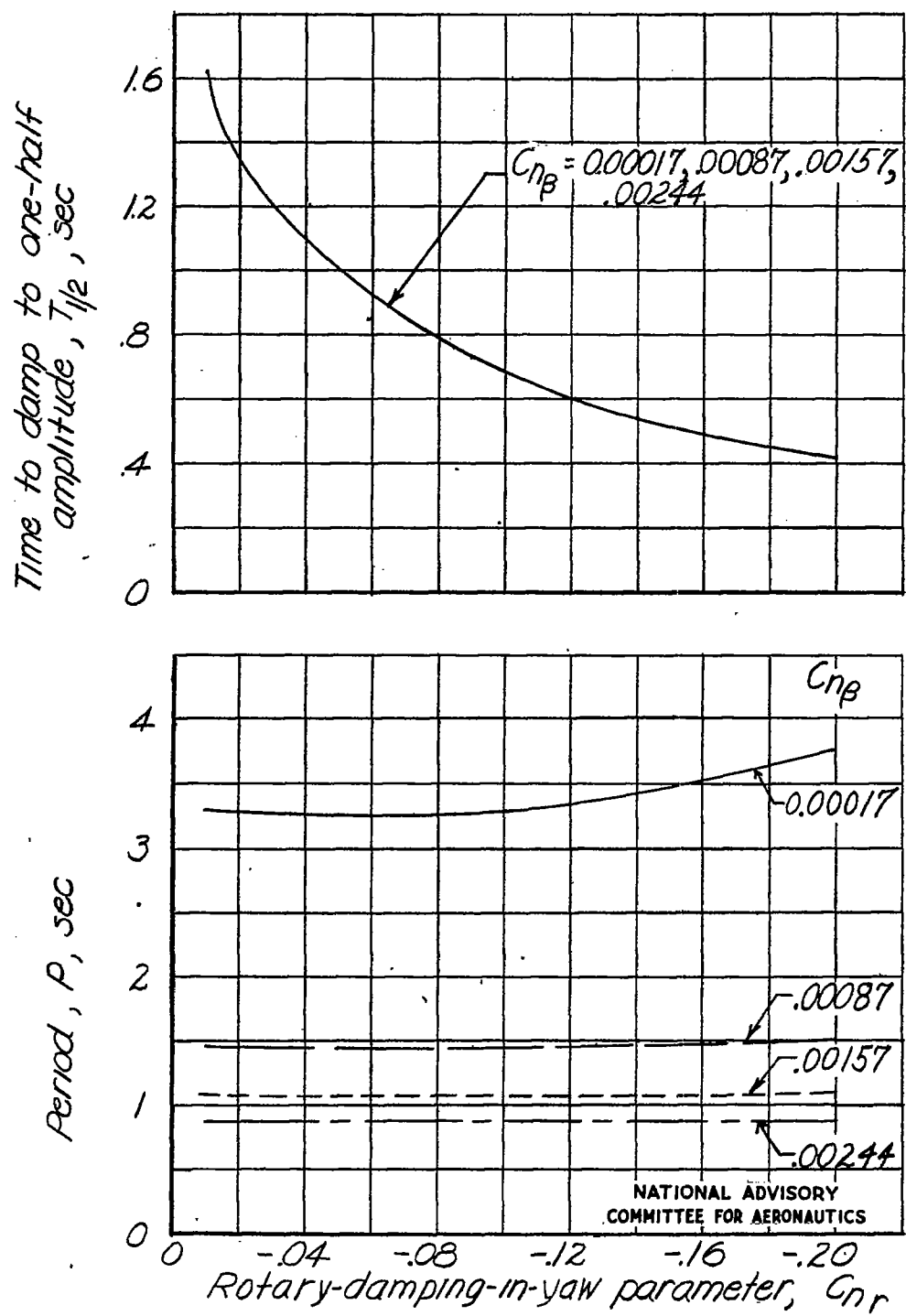


Figure 7.- Calculated effects of varying C_{nr} on the characteristics of the lateral oscillation. $C_{Y\beta} = -0.0105$; $C_L = 0.5$; $C_{l\beta} = 0$.

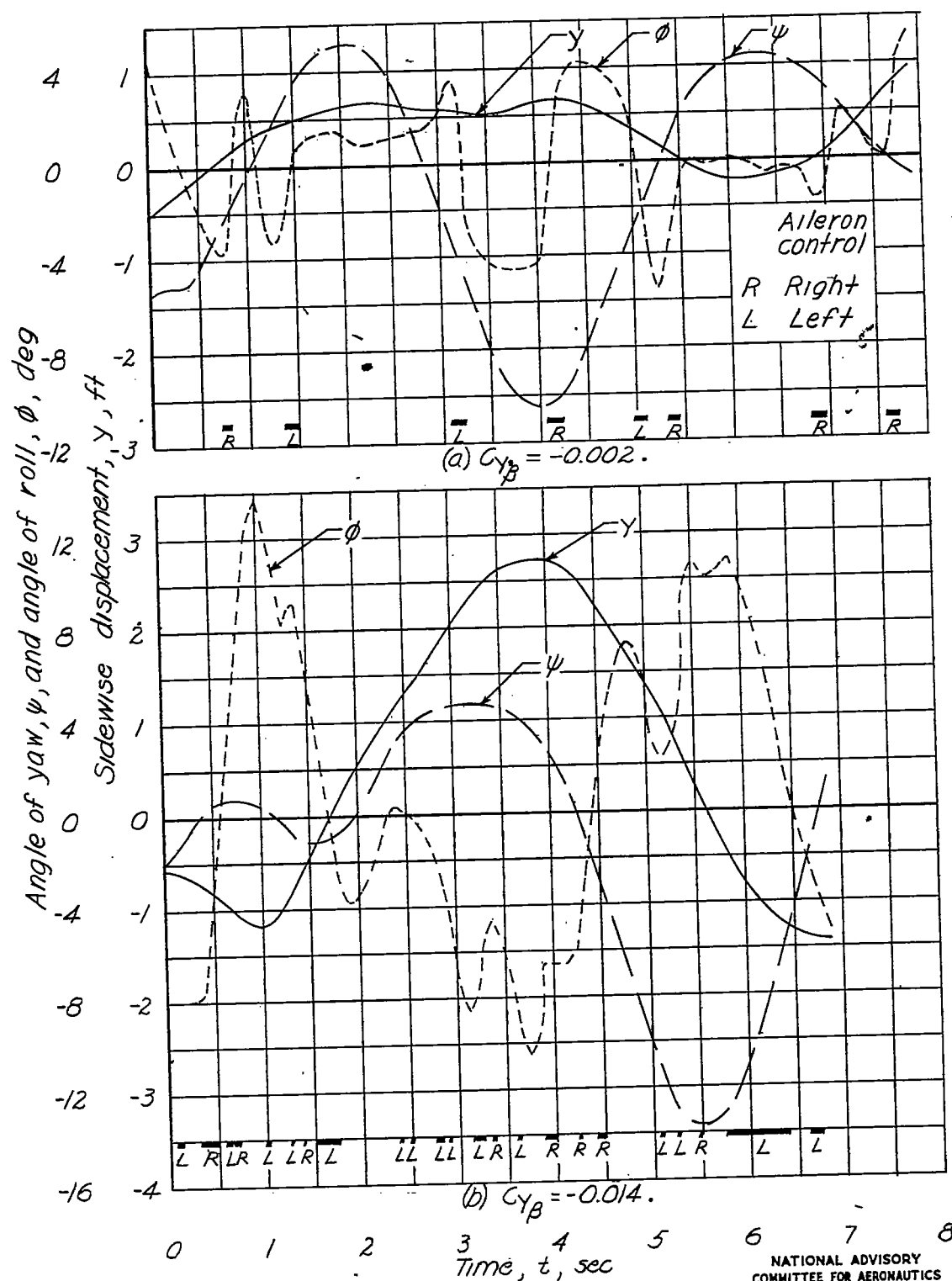


Figure 8.-- Motion-picture records showing flights at small values of $C_{\eta\beta}$ and $C_{\eta r}$ for two values of $C_{Y\beta}$. $C_{\eta\beta} = 0.00014$; $C_{\eta r} = -0.011$.

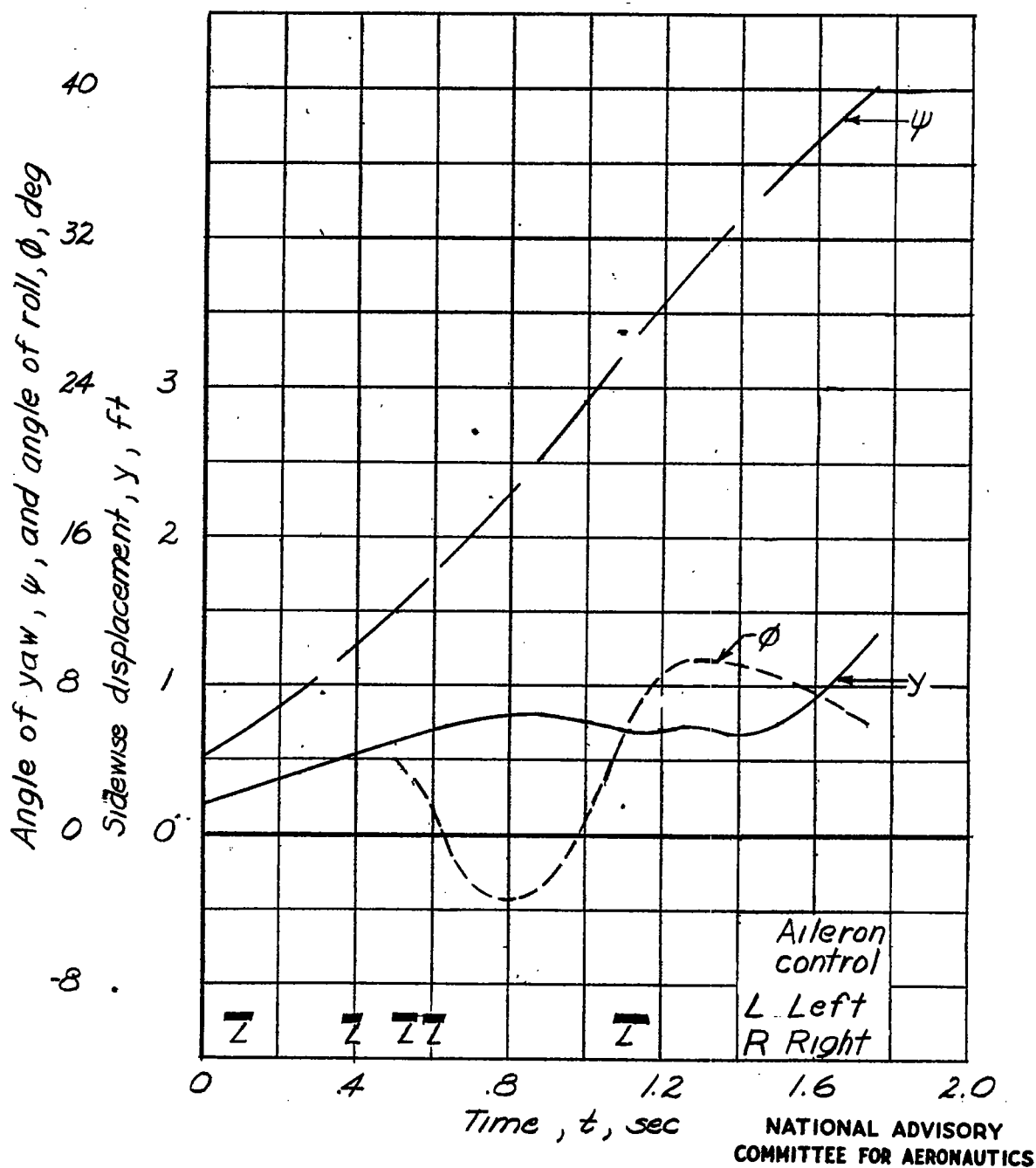


Figure 9. -- Motion-picture record of flight with negative directional stability. $C_{n\beta} = -0.0004$; $C_{Y\beta} = -0.0105$; $C_{nr} = -0.024$; $C_L = 0.5$.